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The Study of Fluid-Elastic Solid Interaction Phenomena using Finite Element Strategies

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One of the goals of the Weapons and Materials Research Directorate of the US Army Research Laboratory (ARL) is to develop propulsion technologies for future gun systems. This effort requires continued improvement of current guns which are already quite close to optimal, and the use of novel, high energy propellants and designs in future weapons. These new designs and propellants make use of next-generation concepts which are not yet well understood. For example, the electrothermal-chemical gun is a hybrid gun which uses a combination of chemical energy and electrical energy to accelerate the projectile. Liquid propellants are also under investigation, raising questions about, for example, the interaction between the liquid propellant (LP) and moving mechanical components in the regenerative liquid propellant gun (RLPG), shown in Figure 1.

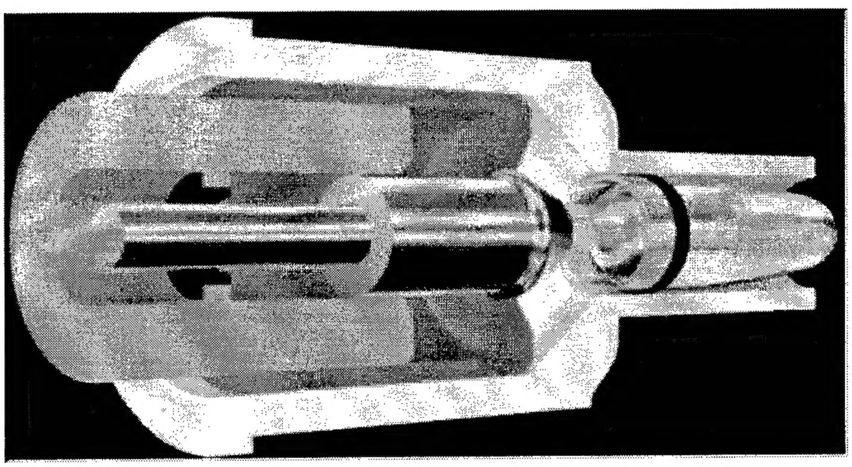

Figure 1. Concept VIC RLPG.

The RLPG is among several propulsion systems under investigation for use in future Army guns. The propellant is a fluid which is initially stored in a reservoir, formed by two pistons and a rear wall. The pistons are initially in contact, separating the LP reservoir from the combustion chamber. During the RLPG firing cycle, the pressure forces in the gun push the pistons toward the rear wall, opening an annular orifice between the pistons. The pressure forces also cause injection of the LP through the orifice and into the combustion chamber. The firing cycle proceeds smoothly, provided the pistons move rearward with no change in direction. The change in direction of motion of the piston is called a piston reversal, and it can result in burning in the LP reservoir.

One class of piston reversals occurs early in the firing cycle, the cause of which has been identified. A second class of reversals, called late reversals, occurs near peak chamber pressure in the firing cycle. The cause of late reversals still eludes researchers. When pressure oscillations in a certain frequency range are strong, late reversals always occur, although they may also occur without strong oscillations at this frequency.

Based on what circumstantial evidence is available, several hypotheses regarding the cause of late reversals have been developed. All of the hypotheses are based on the supposition that the pressure oscillations are accompanied by the vibration of one of the pistons in the gun. The piston has a natural frequency near the frequency of the pressure oscillations associated with late reversals, and it seems likely that a feedback develops between the piston vibration and the pressure oscillations.

One ongoing joint research effort between ARL and the Tezduyar research group at the AHPCRC is the numerical study of the interaction between the vibrating piston and the LP in the RLPG. This effort grew out of a previous joint project of the same team to study LP flow from the liquid reservoir, through the orifice, and into the chamber, which was discussed in the Spring 1994 AHPCRC Bulletin.

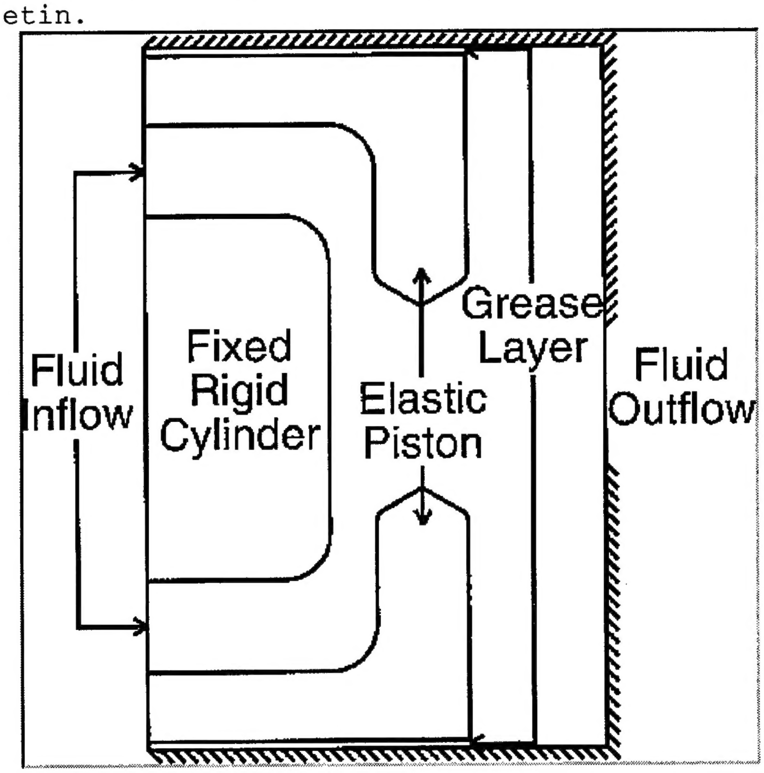

Figure 2. Geometry of test problem.

The simulation of the firing cycle of the RLPG is made difficult by several things. First, as the pistons move, the size and shape of the region of the gun interior occupied by LP, and therefore the size and shape of the computational domain, changes dramatically. Also, the pressure within the gun varies from atmospheric to 300 MPa or higher. The density of the LP varies as much as 5% over this pressure range, and therefore the LP must be treated as compressible. The difficulty is that the high pressure rise in the LP is accompanied by a very small density variation. The coupling between the pressure oscillations and the piston vibration adds further complexity to the problem.

The changes in shape of the computational domain are handled automatically by the Deformable-Spatial-Domain/Stabilized-Space-Time (DSD/SST) formulation, introduced in 1990 by the Tezduyar research group at AHPCRC. By performing a finite element discretization of time, in addition to space, this formulation can automatically handle spatial domains changing in time. It has been used to study a variety of problems, including such geometric complications as free surfaces and two-liquid interfaces, moving bodies, and fluid-structure and fluid-particle interactions. Advanced stabilization methods, namely the streamline-upwind/Petrov-Galerkin and Galerkin/least-squares methods, are used to control the numerical instabilities in the problem.

The model of the solid is based on a Galerkin finite element formulation of linear elastodynamics, which is a well-known and commonly used method. The interface conditions between the piston and the LP are first, that the LP imposes pressure forces on the piston (viscous forces are neglected), and second, the piston position defines the boundary of the LP, and, since a no-slip boundary condition is used, the piston also imposes the fluid velocity along the piston surface.

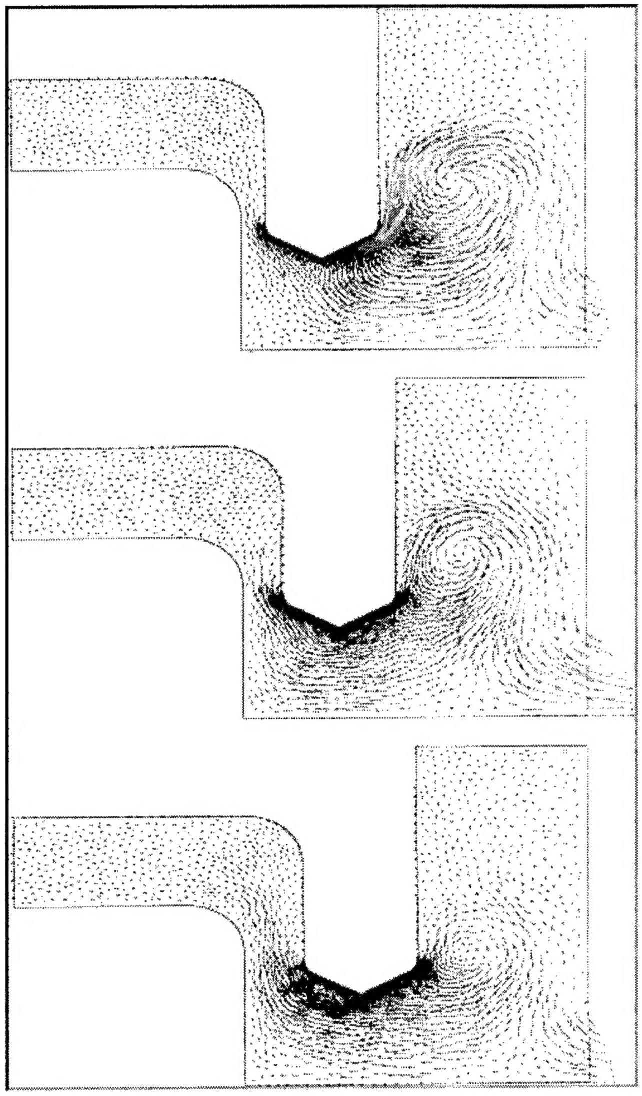

Figure 3. Velocity vectors at times t=1.17 ms, 1.25 ms, and 1.33 ms.

The LP flow field and the piston motion are solved iteratively in each time step. At each time step, first the piston motion is calculated using the LP pressure from the previous time step. The LP flow field is then calculated using that piston motion. A second iteration between the LP flow field and the piston motion is then performed, and the computations proceed onto the next time step.

As the pistons move, and as the computational domain changes in size and shape, the mesh must change as well. During each time step, the mesh is updated based on the motion of the pistons using a special mesh moving method developed by the Tezduyar group at the AHPCRC. A new mesh must be generated occasionally to prevent excessive mesh distortion. This is done by using an automatic mesh generator, also developed by the Tezduyar group

(see the article by Andrew Johnson in the Fall 1994 AHPCRC Bulletin).

The accuracy of the fluid-elastic solid model was demonstrated by modeling a flat plate vibrating both in a vacuum, and with a fluid on one side. Analytical expressions for the natural frequencies of the plate in both cases are available. The computed natural frequencies agree very well with those from the analytical expressions (within 2.4%).

In order to test all of the features of the current model, as a last step before the study of the RLPG firing cycle commences, a test problem, based loosely on the RLPG, was studied. The geometry consisted of a linearly elastic, axisymmetric outer piston surrounding a rigid cylinder (see Figure 2). The cylinder is fixed, while the left end of the piston undergoes a known, sinusoidal motion. Figure 3 shows the velocity vectors at three instants during the simulation.

These test problems were computed on a Cray C90. Similar finite element methods achieve better computational speeds on massively parallel architectures, so a future goal is the parallelization of this model. In view of the good comparison with the test problems and the parallel potential of the method, it appears that the fluid-elastic solid interaction model can aid in the study of the phenomena which occur during the firing cycle of the RLPG.